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CLEAVAGE IN QUARTZ

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ABSTRACT

A new method for studying cleavage in optically uniaxial materials by means of the universal stage was applied to quartz. Statistical analysis of the results indicates that low quartz, when crushed, cleaves most readily parallel to *r* $\{10\bar{1}1\}$ or *z* $\{01\bar{1}1\}$ and next most readily parallel to ξ $\{11\bar{2}2\}$. Less pronounced cleavages exist parallel to *c* $\{0001\}$, *s* $\{11\bar{2}1\}$, *x* $\{51\bar{6}1\}$, *m* $\{10\bar{1}0\}$ and, perhaps, *j* $\{30\bar{3}2\}$ and *a* $\{11\bar{2}0\}$. The direction *d* $\{10\bar{1}2\}$, though reported in the literature, was not observed as a direction for cleavage. The conchoidal fractures of quartz may represent submicroscopic combinations of cleavage planes ξ, *z*, *r*, *c*, *s*, *x*, *m* and *a*.

The number of Si—O bonds cut per unit area was determined for a set of rational planes in the (0001):(11$\bar{2}$0) zone and a second set in the (0001):(10$\bar{1}$0) zone. Of the first set of planes, ξ cut the fewest bonds; of the second set, *r* cut the fewest bonds, cutting even fewer than ξ.

INTRODUCTION

Various cleavage directions have been reported for quartz (Table 1). However, as previously noted (Bloss, 1957, p. 214–215), the existence of several of these, including even the most generally accepted *r* and *z* cleavages, is occasionally questioned. These conflicts of opinion may possibly arise through lack of a clear-cut distinction between the terms fracture and cleavage. According to Fairbairn (1939, p. 358),

"... the terms cleavage and fracture have no precise meaning. Common usage defines cleavage as a rupture which is closely controlled by the structure, and fracture as a rupture in which the structural control is weak."

The "perfection" (*i.e.*, degree of structural control) of surfaces of rupture is generally judged in a qualitative and subjective manner by their degree of planarity, reflectivity, and/or ease of production. Quantitative studies are rarely published. In 1944 von Engelhardt introduced a quantitative study of fracture in low quartz. Bloss (1957) independently developed a similar method in comparing the cleavage tendencies of high and low quartz. To a limited extent, these studies permitted a comparison of the degree of structural control of breakage for those several crystallographic directions which had already been reported as cleavage directions in quartz.

The present study, however, was undertaken since it permits a more certain and detailed crystallographic identification of the preferred directions of fracture in quartz. The methods used could be applied to the study of cleavage in any tetragonal or hexagonal crystal. Unfortunately the method cannot distinguish between the cleavage effects due to correlative forms. Consequently, *r* $\{10\bar{1}1\}$ may not be distinguished from

TABLE 1. SOME REPORTED OBSERVATIONS OF CLEAVAGE IN QUARTZ

Symbol	Index	Name	Source
c	0001	basal pinacoid	Sosman (1927, p. 487); Tsinzerling (1942, p. 556); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 221).
d	$10\bar{1}2$	first-order positive rhombohedron	Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76)
ξ	$11\bar{2}2$	second-order trigonal pyramid	Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76)
r	$10\bar{1}1$	positive rhombohedron	Hauy (1801); Lehmann (1886, p. 609); Mallard (1890, p. 62); Wright and Larsen (1909); Nacken (1916, p. 80); Ichikawa (1915, p. 472): Sosman (1927, p. 427); Schubnikoff and Zintserling (1932, p. 243); Rogers (1933, p. 111); Walker (1935, p. 31); Griggs and Bell (1938, p. 1738); Ingerson and Ramisch (1942, p. 597): von Engelhardt (1944, p. 49); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 221).
z	$01\bar{1}1$	negative rhombohedron	Mallard (1890, p. 62); Sosman (1927, p. 427); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 221).
s	$11\bar{2}1$	second-order trigonal dipyramid	Ichikawa (1915, p. 472); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 222).
x	$51\bar{6}1$	trigonal trapezohedron	Ichikawa (1915, p. 472); Bloss (1957, p. 222).
m	$10\bar{1}0$	unit prism	Ichikawa (1915, p. 472); Sosman (1957, p. 427); Drugman (1939, p. 259); von Engelhardt (1944, p. 50); Anderson (1945, p. 429); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 221).
a	$11\bar{2}0$	second-order prism	Ichikawa (1915, p. 472); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76).

$z\ \{01\bar{1}1\}$, nor $\xi\ \{11\bar{2}2\}$ from $'\xi\ \{2\bar{1}\bar{1}2\}$, $s\ \{11\bar{2}1\}$ from $'s\ \{2\bar{1}\bar{1}1\}$, $a\ \{11\bar{2}0\}$ from $'a\ \{2\bar{1}\bar{1}0\}$, $d\ \{10\bar{1}2\}$ from $'d\ \{01\bar{1}2\}$,[1] $j\ \{30\bar{3}2\}$ from $'j\ \{03\bar{3}2\}$, nor $x\ \{51\bar{6}1\}$ from $'x\ \{6\bar{1}\bar{5}1\}$, $-x\ \{\bar{1}6\bar{5}1\}$ or $-'x\ \{15\bar{6}1\}$. Thus, symbols ξ, s, a, d, j and x are used in the following discussions to indicate not only a specific form but also all the correlative forms. For example, the statement that "cleavage exists parallel to x" is to be construed that cleavage exists parallel to x and/or $'x$, $-x$ and $-'x$.

Acknowledgments

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Materials and Methods

Clear crystals of synthetic quartz, assuredly free of strain, were coarse-crushed at room temperature. Fragments lacking crystal faces were then further crushed in a hammermill. The resultant 80–100 mesh fragments were next strongly irradiated with ultraviolet light to eliminate the possibility of static charges residual from the crushing process. Ultimately, the grains were dusted onto glass slides and cemented in their rest positions with hot, highly fluid, xylol solutions of Canada balsam (*cf.* Bloss, 1957, p. 216).

The slide mounts thus prepared were studied under magnifications of 240× on a 4-axis Leitz universal stage. As described in the previous study (Bloss, 1957, p. 216), measurements were made of θ, the angle between the grain's c-axis and the pole to its plane of rest. In this study, however, the periphery of each grain was additionally examined (by proper tilting and rotation of the stage) for possession of planar fractures at angles to the plane of rest, these being here called "peripheral planes." Such peripheral planes were more common in hammermill-crushed quartz than had been anticipated; of the first 2269 grains examined, 32.4% appeared devoid of peripheral planes, 39.4% possessed one peripheral plane, 22.5% possessed two peripheral planes, and 5.7% possessed three or more

[1] These two correlative forms are symbolized as π and $'\pi$ by Frondel (1962).

peripheral planes. Occasionally these peripheral planes were observed to pass into the curved fracture surfaces typically associated with quartz; occasionally they showed a step effect.

The angular relationship of these peripheral planes to both the *c*-axis and the grain's plane of rest was next determined by standard universal stage methods. A grain possessing one peripheral plane therefore yielded the following angular values (Fig. 1):

(1) θ, as already defined
(2) i, here defined as the interfacial angle between the peripheral plane and the (generalized) fracture surface of rest.
(3) λ, here defined as the angle between the fragment's *c*-axis and the zone-axis (line of intersection) between the peripheral plane and surface of rest.

For a given grain, each additional peripheral plane observed will add a new set of values for i and λ, whereas the value of θ will not change. A grain possessing three peripheral planes would therefore yield three sets of data as follows: (a) θ, i_1, λ_1; (b) θ, i_2, λ_2; and (c) θ, i_3, λ_3.

Those grains which lacked observable peripheral planes—and hence yielded only a θ value—could not be presented by the method next to be

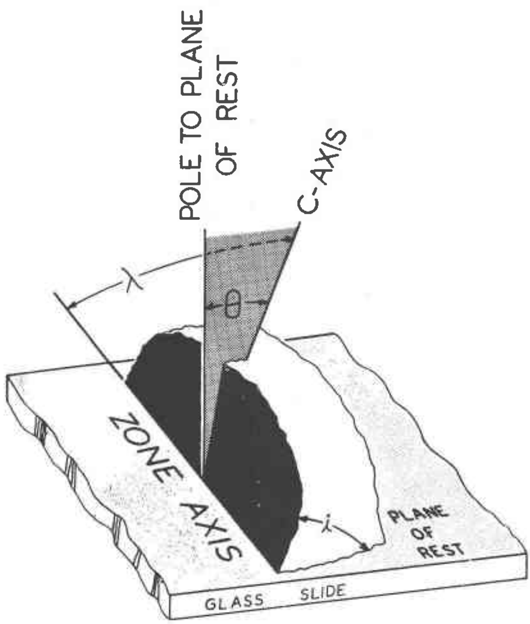

FIG. 1. Highly enlarged quartz fragment. The zone axis common to a peripheral plane (heavily shaded) and the plane of rest is oriented N–S. The significance of angles θ, λ, and i is illustrated—i being the interfacial angle between the peripheral plane and the plane of rest.

described. Hence, after establishing that 32.4% of a random sample of 2269 grains lacked observable peripheral planes, subsequent grains were measured only if observed to possess such planes. Thus only 67.6% of the first 2269 grains (plus the grains subsequently measured) figure in the data next discussed.

Discussion of Results

Method of presentation. The observed data were grouped into five classes according to whether i, the interfacial angle, fell between 32–46°, 46–57°, 57–68°, or 79–90°. The 7573 observations were, as a result, distributed among these classes as follows: (a) 32–46°—720 observations; (b) 46–57°—1020; (c) 57–68°—1412; (d) 68–79°—1891; and (e) 79–90°—2530. The greater frequency of higher interfacial angles may be due, at least in part, to the greater likelihood of observation of such peripheral planes. Peripheral planes making an interfacial angle of less than 32° with the plane of rest were not measurable at all because of the limits of excursion on the horizontal axes of the universal stage.

The individual observations occurring within each of the above classes were plotted in one quadrant of a stereonet as illustrated in Fig. 2. Thus plotted, the observed angles, θ_I and λ_I, define a point (e.g. P in Fig. 2) which denotes the cyclographic projection of the grain's c-axis if the grain is located so that (1) its plane of rest parallels the plane of projection of the stereogram and (2) the zone axis for this plane of rest and the peripheral plane coincides with the N–S radius of the stereogram.

For comparison with the observed data, points have been plotted in a like manner to represent idealized grains resting upon and peripherally bounded by perfectly cleaved faces of the d, ξ, r, z, s, x, m, a, and j forms,

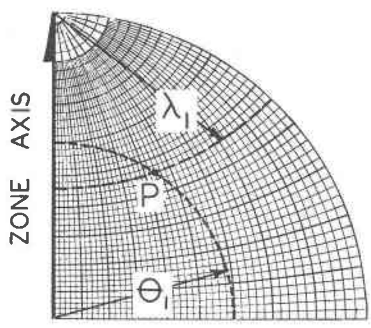

Fig. 2. The use of the stereonet for plotting (from the measured values of θ and λ) the location of the grain's c-axis, if the grain is in "standard position," that is, with its plane of rest parallel to the plane of projection and the zone axis (common to both this plane of rest and the peripheral plane) oriented N–S.

all but j $(30\bar{3}2)$ representing previously reported directions for cleavage. The resultant theoretical points are symbolized on the ensuing stereograms by a large letter (indicating the form of the plane of rest) with a letter subscript (indicating the form of the peripheral plane). Thus a point labelled r_m denotes the cyclographic projection of the c-axis for a grain lying on a perfectly developed r $(10\bar{1}1)$ face and peripherally bounded by a perfectly developed m $(10\bar{1}0)$ face, the $r{:}m$ zone axis being oriented N–S.

The observed data and the theoretical points just described were plotted on quadrants of a stereonet (Figs. 3–6) for four of the five classes of interfacial angles, the plot for the 32–46° class being here omitted since this class later proved to contain too few observations to permit the statistical analysis next to be described.

Statistical analysis. To facilitate statistical analysis of the data, each stereonet quadrant in Figs. 3–6 was divided into 200 cells, all such cells representing equal areas of the fundamental sphere of projection. Next, the accumulation of points (*i.e.*, O_i) in each of the 200 cells of, for example, Fig. 3, was compared with E, the expected cell content under the null hypothesis of isotropic fracture (wherein the data would be equally distributed among the 200 cells). For the data of Fig. 3, chi-square was calculated from the formula

$$\chi^2 = \sum_{i=1}^{200} \frac{(O_i - E)^2}{E} \tag{1}$$

The value for chi-square thus obtained was found to exceed $\chi^2_{.999}$, the value of chi-square for a .999 probability and 199 degrees of freedom as calculated from the formula given by Dixon and Massey (1957, p. 385). The values for chi-square, using equation (1), were also calculated for the data of Figs. 4–6 and in each case exceeded $\chi^2_{.999}$. Thus the null hypothesis that quartz lacks any preferred directions for cleavage was rejected with considerable confidence.

Criteria were next set up to determine (at the 95 per cent confidence level) whether the content of any ith cell (*i.e.* O_i) is significantly above or below the interval about E to be expected from merely chance variations from the null hypothesis. In an approximate manner this was determined for each cell since

$$P\left(-1.96 \leq \frac{O_i - E}{\sqrt{E}} \leq 1.96\right) = 0.95$$

holds to the extent that the $O_i - E/\sqrt{E}$ values are normally distributed and mutually independent. Such is approximately the case; hence, computation of $O_i - E/\sqrt{E}$ for each cell permits recognition (with an expected

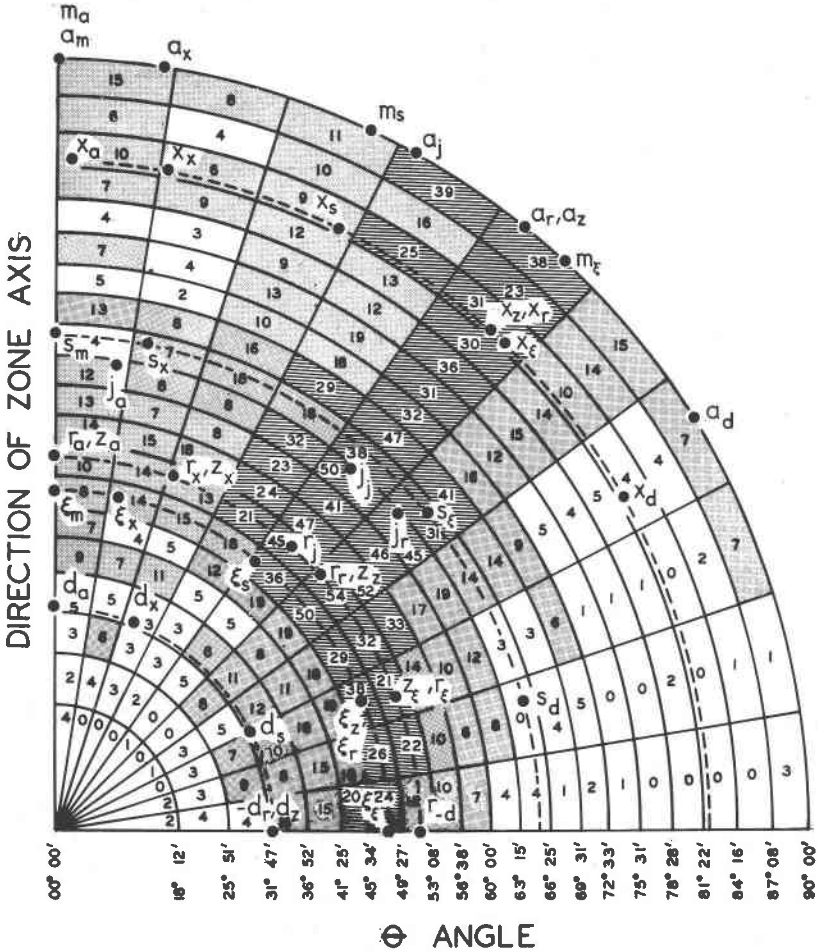

FIG. 3. Plotted data for 2530 observations in which i, the interfacial angle between the peripheral plane and plane of rest, was between 79 and 90°. For comparisons, the plotted positions of combinations of previously reported cleavages are indicated by r_r, s_d, etc. where the letter subscript refers to occurrence as a peripheral plane whereas the larger letter refers to occurrence as a plane of rest. If a grain were to have cleaved precisely parallel to two of the previously reported directions for cleavage, it would plot at one of these black circles. The stereonet quadrant has been divided into 200 cells, each of which represents an equal area on the sphere of projection. The number of observations falling in each cell is indicated near the cell's center whenever possible. Cells containing statistically below-average, average or above-average numbers of observations (at the 95% confidence level) are respectively unshaded, gray-shaded, or horizontally ruled.

ratio of one wrong decision in twenty) of those cells which contain, with respect to the null hypothesis, significantly above-average frequencies

$$\left(\frac{O_i - E}{\sqrt{E}} > 1.96\right),$$

average frequencies

$$\left(-1.96 \leq \frac{O_i - E}{\sqrt{E}} \leq 1.96\right),$$

or below-average

$$\left(\frac{O_i - E}{\sqrt{E}} < -1.96\right)$$

of data. In Figs. 3 to 6 the "above-average cells" thus determined are horizontally ruled, the "average cells" are shaded lightly, and the "below-average cells" are unshaded. For compactness in the tables and discussions to follow, these three cell types will be referred to as (+), (0), and (−) cells, respectively.

Interpretation of data. The (+) cells of Figs. 3–6 generally contain a preponderance of observations. Of the 200 cells in Fig. 3, for example, the 37 (+) cells contain 1282 of the 2530 observations upon which Fig. 3 is based. Conversely, the 72 (−) cells in Fig. 3 contain a total of only 176 observations. The situation for Figs. 4–6 is similar. Even allowing for the one in twenty probability that (+) and (−) cells may actually be (0) types, the dispersal of (+) and (−) cells in Figs. 3–6 indicates, respectively, the existence of regions along which quartz is most likely and least likely to rupture.

Table 2 summarizes the extent to which the theoretical points (*e.g.* r_m, x_r . . . etc.) occur within (+), (0), or (−) cells in Figs. 3–6. Study of Table 2 indicates *d* $\{01\bar{1}2\}$ to be unlikely as a cleavage direction even though it has been previously reported as such. Of 35 theoretical points involving *d* as either a plane of rest or as a peripheral plane, only one is located in a (+) cell whereas 20 were located in (0) cells and 14 in (−) cells. In the face of 14 (−) occurrences, the one instance of a *d* combination in a (+) cell does not seem significant since, on the 95% confidence level used, 1 in 20 could by chance occur in a (+) cell. Since *d* is thus highly unlikely as a possible cleavage direction, the theoretical points representing its combinations with other suspected cleavage forms were disregarded in compiling the remainder of Table 2.

Evidence is rather strong for the existence of the *r* and *z* cleavages in quartz. The distribution of 32.5[1] theoretical points involving *r* or *z* either

[1] Half values were assigned if two theoretical points occurred in the same (+) cell, each combination then "being given half the credit" for the larger frequency of observations within this cell.

TABLE 2. FREQUENCY OF OCCURRENCE OF THE THEORETICAL POINTS REPRESENTING VARIOUS CLEAVAGE COMBINATIONS IN (+), (0), OR (−) CELLS IN FIGS. 3–6

	Previously described or suspected cleavages																										
	d			ξ[1]			r, z[1]			j[1]			s[1]			x[1]			m[1]			a[1]		
	+	0	−	+	0	−	+	0	−	+	0	−	+	0	−	+	0	−	+	0	−	+	0	−
Occurrence as a plane of rest	0	9	7	5	11	0	8	9	0	5	8	0	4	7	1	2	18	0	2	7	0	2	4	0
Occurrence as a peripheral plane	1	11	7	8.5	6	0	8.5	7	0	5	11	0	2.5	11	0	2.5	19	0	1	7	1	0	8	0
Total occurrences	1	20	14	13.5	17	0	16.5	16	0	10	19	0	6.5	18	1	4.5	37	0	3	14	1	2	12	0

[1] Combinations with d are omitted.

as a plane of rest or as a peripheral plane in Figs. 3–6 was: (+), 16.5; (0), 16; and (−), none. The absence of theoretical points involving r or z from (−) cells provides further evidence for the existence of cleavage parallel to these directions. Furthermore the theoretical point indicating cleavage combinations r_r, r_z, z_r or z_z falls in the cell of greatest data concentration of all the cells in Figs. 3 to 6.

The ξ $\{11\bar{2}2\}$ direction is also corroborated as a plane of cleavage. As Table 2 illustrates, theoretical points involving ξ were distributed among the cells of Figs. 3–6 as follows: (+) 13.5; (0), 17; and (−), none. Local

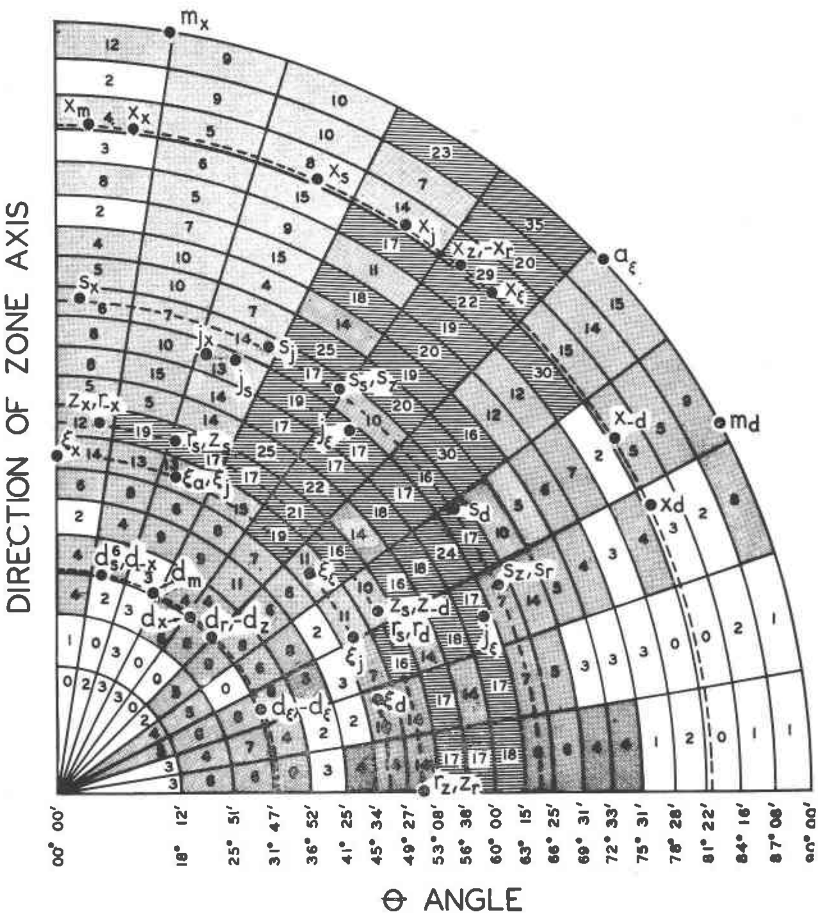

FIG. 4. Plotted data for 1891 observations in which i, the interfacial angle between the peripheral plane and plane of rest, was between 68 and 79°. The conventions observed are the same as in Fig. 3.

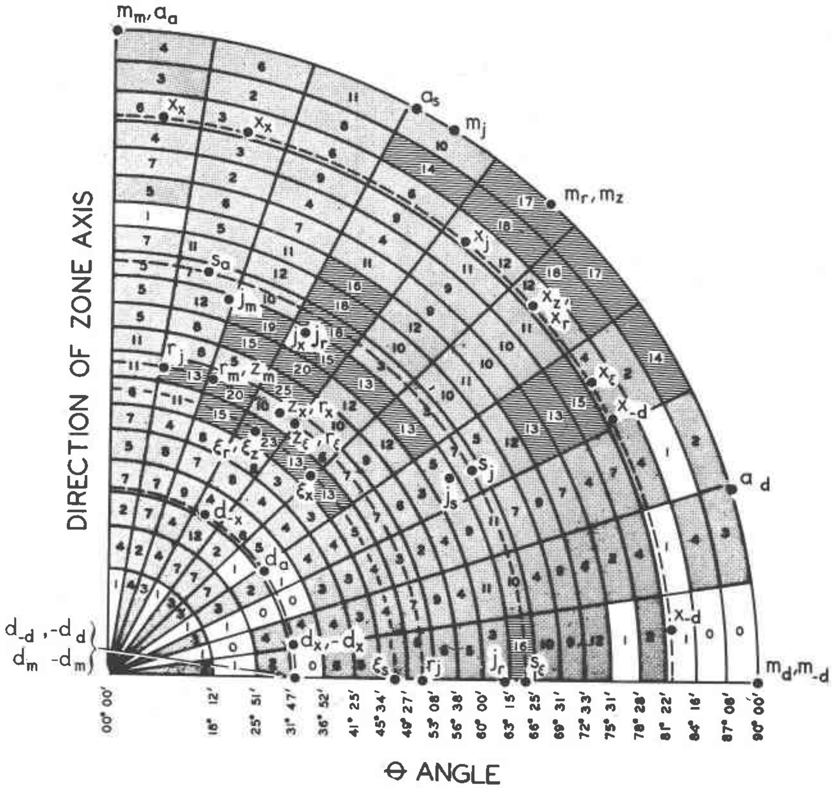

FIG. 5. Plotted data for 1412 observations in which *i*, the interfacial angle between the peripheral plane and plane of rest, was between 57 and 68°. The conventions observed are the same as in Fig. 3.

highs in the accumulations of data sometimes occur near theoretical points involving ξ, particularly when ξ is in combination with *r* or *z* (Fig. 5). However, compared to the *r* and *z* directions, ξ seems somewhat inferior as a direction for cleavage.

Concentrations of data were observed in Figs. 3–6 which seemed best explained by assuming that quartz has a tendency to cleave parallel to *j* $\{30\bar{3}2\}$. This cleavage, not previously reported in the literature (to the writers' knowledge), forms theoretical points distributed among the cells of Figs. 3–6 as follows: (+), 10; (0), 19; and (−), none. Thus *j* is a possible cleavage direction for quartz since the ten occurrences in (+) cells seem significantly above the number expected.

Evidence in Figs. 3–6 for the existence of *s*, *x*, *m*, and *a* cleavages is less conclusive than that for *r*, *z*, and ξ. Theoretical points involving the *s* cleavage, however, occur more frequently in (+) cells than may be attributed to chance (Table 2). The single occurrence of the theoretical point s_m in a (−) cell in Fig. 3, is possibly attributable to chance. Of 41.5 theoretical points involving the x cleavage, 4.5 occur in (+) cells (Table 2) whereas only 2 would have been expected on the basis of chance variations from the null hypothesis of no preferred directions of cleavage. The m cleavage also shows two more occurrences in (+) cells (Table 2) than can be attributed to chance. The single occurrence of a theoretical point involving m in a (−) cell is the s_m point previously attributed to chance. Theoretical points involving the a cleavage occur in (+) cells only slightly

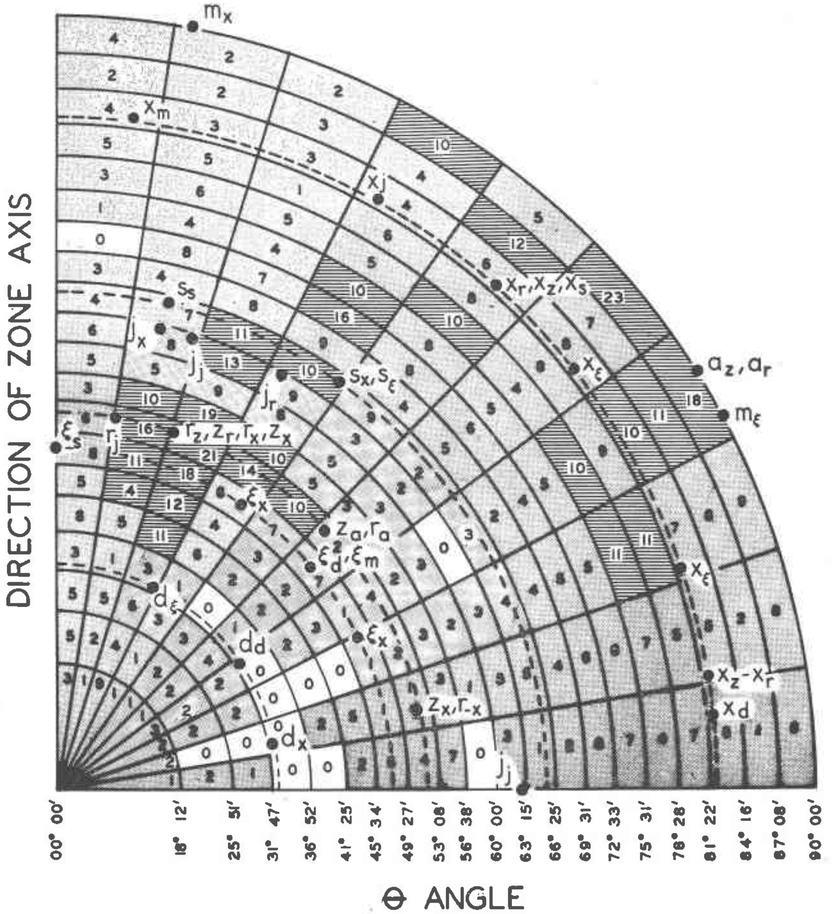

FIG. 6. Plotted data for 1020 observations in which i, the interfacial angle between the peripheral plane and the plane of rest, was between 46 and 57°. The conventions observed are the same as in Fig. 3.

more frequently than is attributable to chance. Thus, although *s*, *x*, and *m* appear to be cleavage directions for quartz, the evidence for cleavage parallel to *a* is slightly less convincing.

In Figs. 3–6 the (+) cells tend to be concentrated in particular areas rather than being spottily distributed throughout; this is particularly true for Figs. 3 and 4 wherein the (+) cells are distributed in the areas linking certain theoretical points—for example, between ξ_ξ, ξ_z, ξ_r, z_ξ, r_ξ, r_z, z_r, s_ξ, x_z, x_r and m_ξ in Fig. 3—in a manner that suggests that the data represent measurements on quartz fragments which rest on slightly conchoidal surfaces or on surfaces consisting of cooperative breakage along two or more cleavage directions. The well known conchoidal fractures of quartz seem most likely to represent cooperative breakage along two or more cleavage directions (on such an intimate scale that curved rather than visibly stepped surfaces result). The distribution of the (+) cells between the theoretical points in Figs. 3–6 probably indicates the broad limits within which the conchoidal fracture of quartz undergoes structural control.

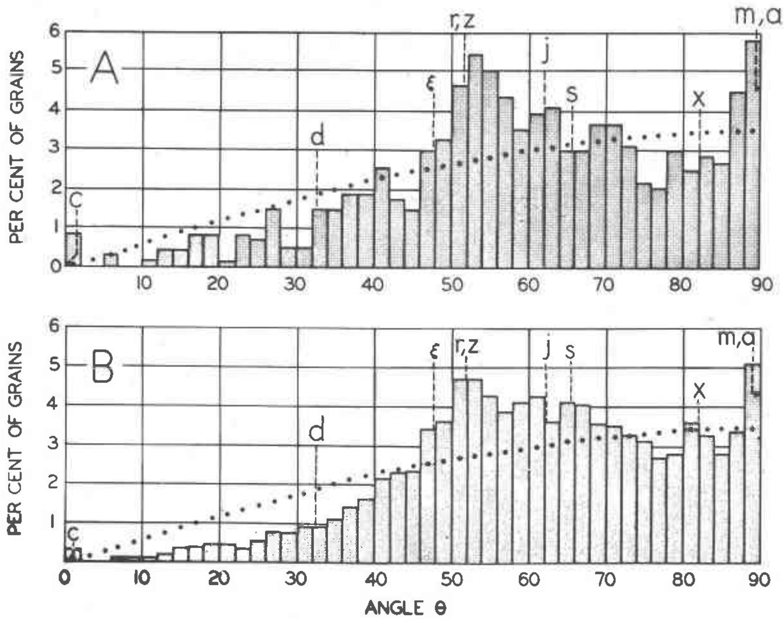

FIG. 7. (A) Histogram indicating the frequency of observation of particular values of θ for 735 grains in which peripheral cleavage planes were not observed. The dashed lines indicate where data from grains resting on particular cleavages would plot. The isotropic distribution curve previously discussed by Bloss (1957) is shown by a dotted line.

(B) Histogram indicating the frequency of observation of particular values of θ for 5804 grains, most of which possessed peripheral planes.

The basal cleavage, c {0001}, embraces only one direction in its form. Consequently it forms too few "theoretical points" (in combination with other cleavages) to permit an adequate study by the zonal method embodied in Figs. 3 to 6. Fortunately, the existence of a basal cleavage can be unequivocably demonstrated by histograms which show the relative frequency of observation of θ in grains of crushed quartz. Two such histograms were prepared, one for crushed grains on which peripheral planes were not observed (Fig. 7A), a second for grains in which they were (Fig. 7B). The dotted line in each indicates the class heights to be expected if quartz possessed no cleavage at all, the sine-curve nature of this distribution having been previously discussed by Bloss (1957). In both histograms the 0–2° class projects above the sine curve and thus indicates the presence of the basal cleavage c. This is more pronounced in Fig. 7A than in Fig. 7B, a fact which suggests that a basal cleavage is developed on a grain only when it is oriented crystallographically at an angle to the stress such that this stress can be resolved almost entirely along the (0001) plane. This was further corroborated by subdividing the data of Fig. 7B into different histograms, one histogram for grains in which only one

TABLE 3. BOND DENSITIES FOR SURFACES IN THE (0001):(11$\bar{2}$0) ZONE

Pole∧c-axis	Bonds per Å² of surface	Pole∧c-axis	Bonds per Å² of surface
0°[1]	.0961	52° 51′	.0696
4° 12′	.0958	54° 20′	.0709
8° 21′	.0951	56° 11′	.0726
12° 25′	.0938	58° 07′	.0742
16° 21′	.0922	60° 08′	.0757
20° 8′	.0902	62° 14′	.0773
23° 45′	.0879	64° 26′	.0788
27° 10′	.0855	66° 42′	.0802
30° 24′	.0829	69° 03′	.0816
33° 25′	.0802	71° 29′	.0828
36° 15′	.0775	73° 59′	.0839
38° 58′	.0747	76° 31′	.0849
41° 21′	.0721	79° 10′	.0858
43° 38′	.0695	81° 50′	.0865
45° 45′	.0670	84° 32′	.0869
47° 43′[2]	.0646	87° 16′	.0872
49° 33′	.0665	90°[3]	.0873
51° 16′	.0681		

[1] Corresponds to c (0001).
[2] Corresponds to ξ (11$\bar{2}$2).
[3] Corresponds to a (11$\bar{2}$0).

TABLE 4. BOND DENSITIES FOR SURFACES IN THE (0001):(10$\bar{1}$0) ZONE

Pole∧c-Axis	Bonds per Å² of surface	Pole∧c-Axis	Bonds/per Å²
0°[1]	.0961	57° 03′	.0635
5° 11′	.0957	58° 31′	.0645
10° 27′	.0945	59° 52′	.0654
15° 14′	.0926	61° 41′	.0666
19° 57′	.0903	63° 33′	.0677
24° 24′	.0875	65° 30′	.0688
28° 34′	.0844	67° 29′	.0699
32° 25′	.0811	69° 33′	.0709
35° 58′	.0777	71° 39′	.0718
39° 14′	.0744	73° 49′	.0726
42° 13′	.0711	76° 02′	.0734
44° 56′	.0680	78° 17′	.0741
47° 26′	.0650	80° 35′	.0746
49° 42′	.0621	82° 55′	.0751
51° 47′[2]	.0594	85° 18′	.0754
53° 41′	.0609	87° 38′	.0756
55° 26′	.0623	90°[3]	.0756

[1] Corresponds to c (0001).
[2] Corresponds to r (10$\bar{1}$1) or z (01$\bar{1}$1).
[3] Corresponds to m (10$\bar{1}$0).

peripheral plane was observed, a second for grains in which two peripheral planes were observed, and a third for grains possessing three or more peripheral planes. The height of the 0–2° class was observed to decrease steadily in the histograms as the number of observed peripheral planes increased.

Fig. 7A (735 observations) does not readily illustrate the influence of the s and x cleavages, whereas Fig. 7B (5804 observations) does. The fewer observations on which Fig. 7A is based is probably the reason. Evidently a rather large number of observations is required before the effect of minor cleavages such as s and x becomes apparent in these histograms.

STRUCTURAL CONSIDERATIONS

From a projection of the quartz structure on a plane perpendicular to the (0001):(11$\bar{2}$0) zone axis, the number of Si—O bonds cut per unit area was determined for a series of rational planes in the (0001):(11$\bar{2}$0) zone (Table 3 and Fig. 8, curve A). Of these planes, ξ (11$\bar{2}$2) cuts the fewest bonds per unit area and thus marks the minimum in Curve A. From a second structural projection on a plane perpendicular to the (0001):(10$\bar{1}$0) zone axis, the Si—O bonds cut by a series of rational planes in this zone was also determined (Table 4 and Fig. 8, Curve B). Of these planes, *r* (10$\bar{1}$1) cuts fewest bonds per unit area and marks the minimum for Curve B, cutting even fewer bonds than the previously discussed ξ. Consequently, on the basis of bond density, cleavages *r* (or *z*) and ξ would be anticipated from the quartz structure, *r* being superior to ξ. This is, in fact, in agreement with the observations.

Factors other than the number of Si—O bonds cut per unit area also affect the ease of rupture along a particular plane in quartz. To illustrate, the observed data (Fig. 7) indicate *c* {0001} to be more frequent as a plane of rupture than planes for which θ lies between 2° and 14°—yet, as Fig. 8 illustrates, *c* {0001} cuts more bonds per unit area. Thus it seems likely that a factor such as the angle of the Si—O bond to the prospective surface of rupture may also be operative.

Von Engelhardt (1944) and Hoffer (1961) have considered the effect of bond directions. Hoffer (1961, p. 85) defines a "cohesive force field" and then assumes that (1) the twelve different Si—O bonds coincide with directions for maxima in this field whereas (2) the normals to 24 (irrational) planes defined by two intersecting bonds—that is, by trios of neighboring nuclei such as O—Si—O or Si—O—Si—represent minima in

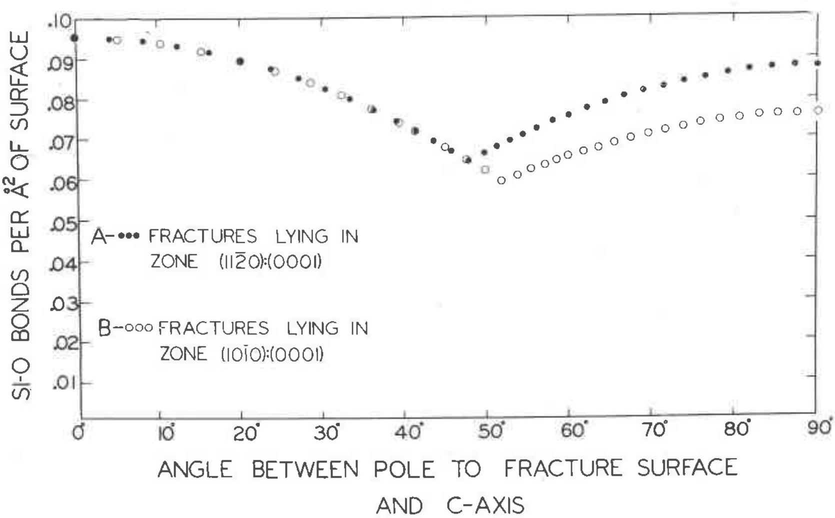

FIG. 8. The density of Si—O bonds broken per square angstrom of fracture surface as calculated from the structure of quartz for (*A*) a family of fractures lying in the (11$\bar{2}$0) : (0001) zone but at various angles of tilt to the *c*-axis and (*B*) a family of fractures lying in the (10$\bar{1}$0) : (0001) zone and at various angles of tilt to the *c*-axis. The minimum for curve *A* corresponds to cleavage parallel to ξ; the minimum for curve *B* corresponds to cleavage parallel to *r* or *z*.

this field. From the atomic parameters for Si and O in the low quartz structure, Hoffer computed (1) the directions of the Si—O bonds, (2) the indices of the 24 irrational planes and (3) the sines of the angles of intersection between each Si—O bond and, successively, each irrational plane. He accepts the 24 irrational planes (whose θ values are 29° 19′, 47° 38′, 51° 46′, 61° 38′ and 78° 56′) to be potential fracture planes, and uses the "absolute sum of sines of angles of intersection with bonds" to determine which would perhaps be better. For one irrational plane, θ equals 51° 46′, a value like that to be expected for cleavage along *r* $\{10\bar{1}1\}$; however, plotted on a stereogram, the two planes differ in ϕ angle by 30°. Hoffer suggests that in histograms like those in Fig. 7, peaks near 52° may be the expression of the irrational plane rather than the *r* $\{10\bar{1}1\}$ cleavage. However, this present study provides more data than the histogram method and corroborates the existence of cleavage parallel to *r* $\{10\bar{1}1\}$. Further evidence in support of cleavage parallel to *r* or *z*, rather than to the irrational plane suggested by Hoffer, may be found in: (1) the numerous reports of *r* cleavage in the literature (cf. Table 1) and (2) broken, hand-specimen-sized, single crystals of quartz in which interrupted cleavage surfaces reflect light simultaneously with (and are therefore parallel to) the *r* and *z* crystal faces present on the specimen.

Conclusions

1. Low quartz cleaves most readily parallel to *r* $\{10\bar{1}1\}$ or *z* $\{10\bar{1}1\}$ and next most readily parallel to ξ $\{11\bar{2}2\}$.

2. These directions break the least number of Si—O bonds of all planes in the (0001):(10$\bar{1}$0) and (0001):(11$\bar{2}$0) zones, respectively.

3. Less pronounced cleavages exist parallel to *c* $\{0001\}$, *s* $\{11\bar{2}1\}$, *x* $\{51\bar{6}1\}$, *m* $\{10\bar{1}0\}$, and, perhaps, *j* $\{30\bar{3}2\}$ and *a* $\{11\bar{2}0\}$.

4. The direction *d* $\{10\bar{1}2\}$ is unlikely as a cleavage unless direction of stress is closely controlled.

5. The conchoidal fracture of quartz is, to a degree, structurally controlled. The curved surfaces may represent submicroscopic combinations of cleavage planes ξ, *z*, *r*, *c*, *s*, *x*, *m*, and *a*.

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